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HYDRAULIC FLIP BEHAVIOR IN TYPICAL LIQUID ROCKET OPERATING REGIMES

Thomas J. C. Chew

Air Force Rocket Propulsion Laboratory
Edwards Air Force Base, California

July 1973

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T.J.C. CHEW

TECHNICAL REPORT AFRPL-TR-72-127

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13. ABSTRACT

An experimental investigation on hydraulic flip behavior at typical liquid rocket injector design and operating conditions was completed. Both nitrogen tetroxide and water were used as test fluids. The results were analyzed to show the effect of chamber pressure, orifice L/D, orifice diameter and cross-flow velocity on the occurrence of hydraulic flip. Comparison of experimental results with the theoretical models developed by Ito was made. It was concluded that chamber pressure and orifice L/D strongly affect the occurrence of hydraulic flip while orifice diameter and cross-flow velocity influence hydraulic flip to a much lesser degree. The theoretical models were found to be inadequate for predicting hydraulic flip. The conditions for the occurrence of flip appear nearly the same for both nitrogen tetroxide and water.

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FOREWORD

The work described in this report was performed in direct response to SAMSO TN 302-69-11. The effort was conducted within the Combustion Group, Special Projects Branch, Technology Division, AFRPL, under Project 573010CG. Mr. Thomas J.C. Chew was the Project Engineer and Mr. Roger L. Rollins was the Test Engineer. The time period covered by this report is from April 1971 to August 1972.

The material presented herein provided the basis for a technical paper presented at the 9th JANNAF Combustion Meeting, Monterey, California, September 11-15, 1972.

This technical report has been reviewed and is approved.

C. C. CHRISMAN, Major, USAF
Chief, Special Projects Branch
Technology Division
Air Force Rocket Propulsion Laboratory

ABSTRACT

An experimental investigation on hydraulic flip behavior at typical liquid rocket injector design and operating conditions was completed. Both nitrogen tetroxide and water were used as test fluids. The primary test variables and the range and steps of variation for each variable were as follows:

Orifice diameter - 0.050 in., 0.072 in., 0.110 in.

Orifice L/D - 1, 2, 4, 6, 8

Chamber pressure - 0 psig, 200 psig, 400 psig, 600 psig, 800 psig

Cross-flow velocity - 0 ft/sec, 5 ft/sec, 10 ft/sec, 15 ft/sec, 20 ft/sec

A single orifice was used in each test. The chamber pressure was simulated with gaseous nitrogen. The results were analyzed to show the effect of each primary test variable on the occurrence of hydraulic flip. Comparisons of experimental results with the theoretical models developed by Ito were also made. It was concluded that chamber pressure and orifice L/D strongly affect the occurrence of hydraulic flip while orifice diameter and cross-flow velocity influence hydraulic flip to a much lesser degree. The theoretical models were found to be inadequate for predicting hydraulic flip. The conditions for the occurrence of flip appear nearly the same for both nitrogen tetroxide and water.

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NOMENCLATURE

C_{co}	=	Contraction coefficient at vena contracta, dimensionless
C_d	=	Orifice discharge coefficient, dimensionless
C_{dA}	=	C_d value after the occurrence of hydraulic flip, dimensionless
C_{dB}	=	C_d value before the occurrence of hydraulic flip, dimensionless
D_o	=	Orifice diameter, in.
f	=	Friction factor, dimensionless
L/D	=	Orifice length to diameter ratio, dimensionless
$(L/D)cr$	=	Critical orifice L/D below which detached flow will occur, dimensionless
P	=	Pressure, $lb/in.^2$
P_c	=	Chamber pressure or back pressure, $lb/in.^2$
P_v	=	Fluid vapor pressure, $lb/in.^2$
ΔP_f	=	Orifice pressure drop required for hydraulic flip to occur, $lb/in.^2$
$\Delta(\Delta P_f)$	=	An increment of ΔP_f, $lb/in.^2$
ΔP_o	=	Orifice pressure drop, $lb/in.^2$
ΔP_{uf}	=	Orifice pressure drop at which unflipping (flow re-attachment) will occur, $lb/in.^2$
R_{ed}	=	Reynolds number based on diameter, dimensionless
T	=	Fluid temperature, ^oF
T_f	=	Fluid temperature at the hydraulic flip point, ^oF
ΔT	=	An increment of fluid temperature, ^oF
V_c	=	Cross-flow velocity, ft/sec
$\bar{n}$	=	Pressure recovery factor, dimensionless

SECTION I

INTRODUCTION

Past experience has shown that circular orifices with sharp-edge inlets, such as those commonly found in liquid rocket injectors, may flow attached or detached at their exit with corresponding changes to their discharge coefficients of 20 percent or more. The transition from attached to detached flow is called hydraulic flip. It is usually manifested in liquid rocket engines by changes in mass and mixture ratio distributions (Reference 1) which are demonstrated causes for performance degradation, combustion instability and off-optimum propellant utilization.

The hydraulic flip phenomenon was investigated in the past (References 2, 3, and 4) primarily in connection with combustion efficiency and instability studies. Generally water was used as a propellant simulant and testing was conducted at low chamber pressure or atmospheric pressure conditions. Experimental test results did not indicate a definite link between hydraulic flip and combustion instability. Therefore, until recently, the interest in hydraulic flip existed only at a very low level. The interest was recently intensified because of unexpected performance degradation and mixture ratio shift problems encountered with operational liquid rocket engines. It was theorized that hydraulic flip could be the cause of these problems.

Originally, hydraulic flip was believed to be caused solely by fluid cavitation resulting when the static pressure at the orifice flow vena contracta decreased below the fluid vapor pressure. However, this condition can be met only when the injector pressure drop exceeds a critical value, and can occur only during engine start transients or low chamber pressure engine operation. For this case then, it is generally expected that the fluid would flow detached in the orifice until sufficient chamber pressure is attained to stop the cavitation and obtain attached flow. Thus, hydraulic flip has never been previously considered as a serious injector design problem. However, J. Ito (Reference 5) recently developed a theoretical model which shows that hydraulic flip can occur in orifices with marginal length-to-diameter (L/D) ratios, even if the static pressure at the vena contracta is well above the fluid vapor pressure. If this is true, hydraulic flip should be an important consideration in liquid rocket engine design and operation.

The objectives of this investigation were to define the influence of primary injector design and operating parameters on hydraulic flip with emphasis on realistic chamber pressure conditions and to check the applicability of the theoretical models formulated by Ito.

SECTION II

TEST PROGRAM

A series of 31 test conditions, covering four test variables at four to five incremental steps, was investigated with each of two test fluids. Both N_2O_4 and water were tested. The test variables investigated were orifice diameter, orifice length-to-diameter ratio (L/D), chamber pressure, and cross-flow velocity in the propellant feed channel behind the injector face plate. The range of variation of each test variable is typical of the range of current interest to the Air Force, as listed in Table I.

TABLE I. BASIC TEST MATRIX

Orifice Diameter (inches)	Orifice L/D	Back Pressure (psig)	Cross-Flow Velocity (ft/sec)
0.050	2	200	0
0.050	1,4,6,8	200	0
0.050	2	0,400,600,800	0
0.050	2	200	5,10,15,20
0.072,0.110	2	200	0
0.072	1,4,6	200	0
0.072	2	0,400,800	0
0.072	2	200	10,20
0.110	1,4,6	200	0
0.110	2	0,400,800	0
0.110	2	200	10,20

In addition, a short series of tests was also accomplished to check out the validity of the experimental test set-up and to provide immediate support to the Space and Missile Systems Organization (SAMSO) Titan III program. The test conditions covered by this series of tests are listed in Table II.

TABLE II. SPECIAL TEST MATRIX

Orifice Diameter (inches)	Orifice L/D	Back Pressure (psig)	[illegible]-Flow Velocity (ft/[illegible])
0.072	ASME sharp-edge	300	0
0.072	1	800	0
0.072	2	800	0
0.072	4	800	0
0.072	6	800	0
0.072	2	100	0

It should be noted that no attempt was made to condition either the temperature of the test fluids or the temperature of the chamber pressurizing gas. Ambient temperature gaseous nitrogen was used exclusively for chamber pressure (back pressure) simulation.

SECTION III

EXPERIMENTAL APPARATUS AND PROCEDURES

TEST HARDWARE

The basic test hardware consisted of an injector body, a series of removable orifice plates and a series of removable back plates as shown in Figures 1, 2 and 3, respectively. The hardware was fabricated from 304 stainless steel. In the center of the 2.0-inch thick injector body, open to the front and back faces, was a 1.0 inch by 3.73 inch rectangular port. To prepare for each test, the front face was covered by a selected orifice plate to provide a specific orifice configuration, while the back face was covered by a selected backplate to provide a specific cross-flow area. The orifice plates and backplates which were fabricated for this program are listed in Tables III and IV.

The ability to change the cross-flow area from test to test was required to vary the cross-flow velocity from test to test in investigating the effect of cross-flow velocity on hydraulic flip. A perforated plate was located down stream of the propellant inlet port (inside the rectangular port of the injector body) to provide a more uniform cross-flow velocity behind the injector orifice plate. The original design of the plate had three 0.1 inch x 0.4 inch rectangular flow ports, but was later substituted with a plate having fifty 0.050 inch diameter orifices. No significant change in the hydraulic flip test results were noted as a result of this change. A provision for bypassing propellant out of the injector body was also included for use in maintaining a constant cross-flow velocity for tests during which the velocity was the primary variable (see Table I).

A back pressure chamber, eight inches in diameter and fabricated out of stainless steel, was used to simulate various chamber pressure levels. The chamber is approximately 20 inches long and has a drainage port of

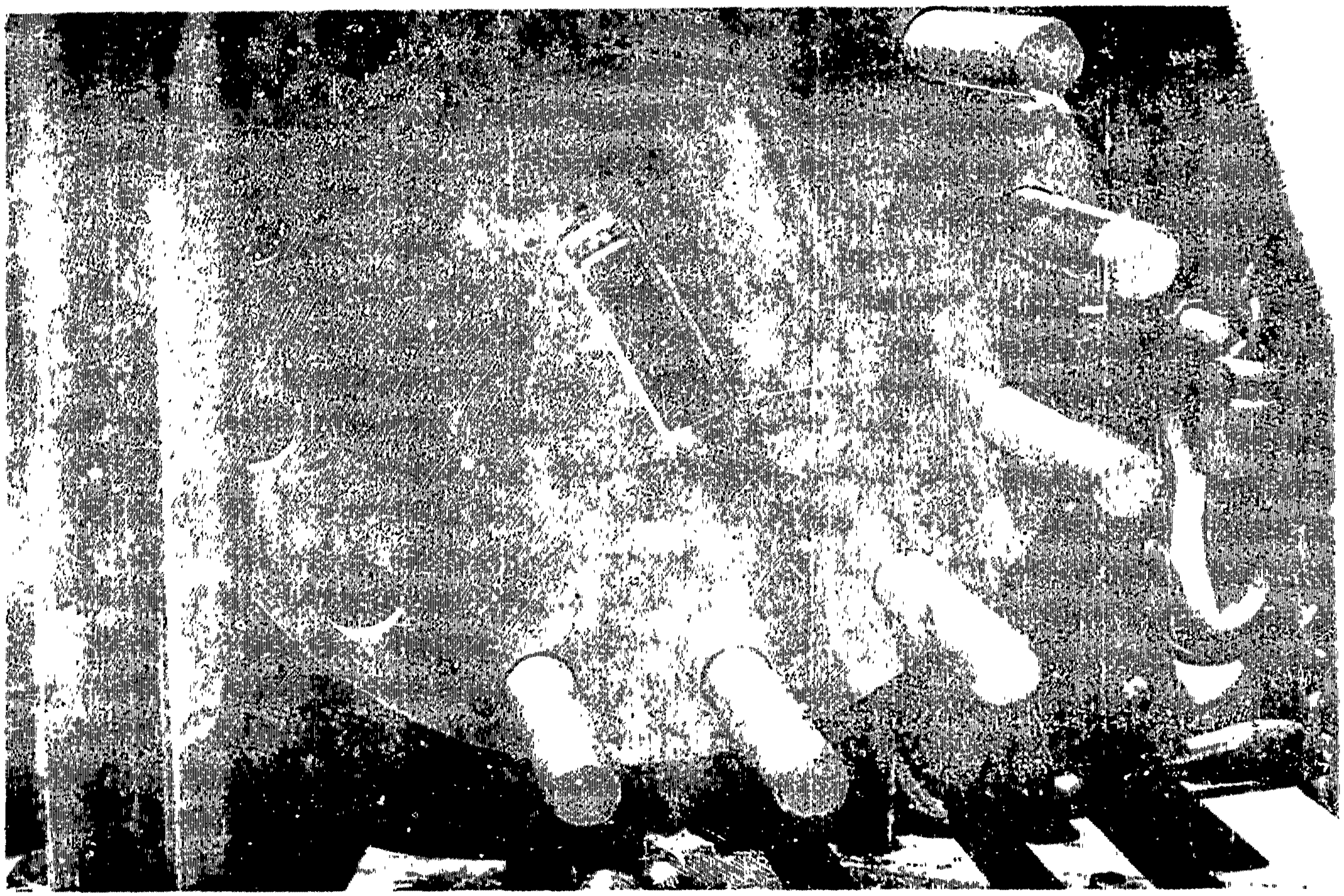


Figure 1. Injector Body

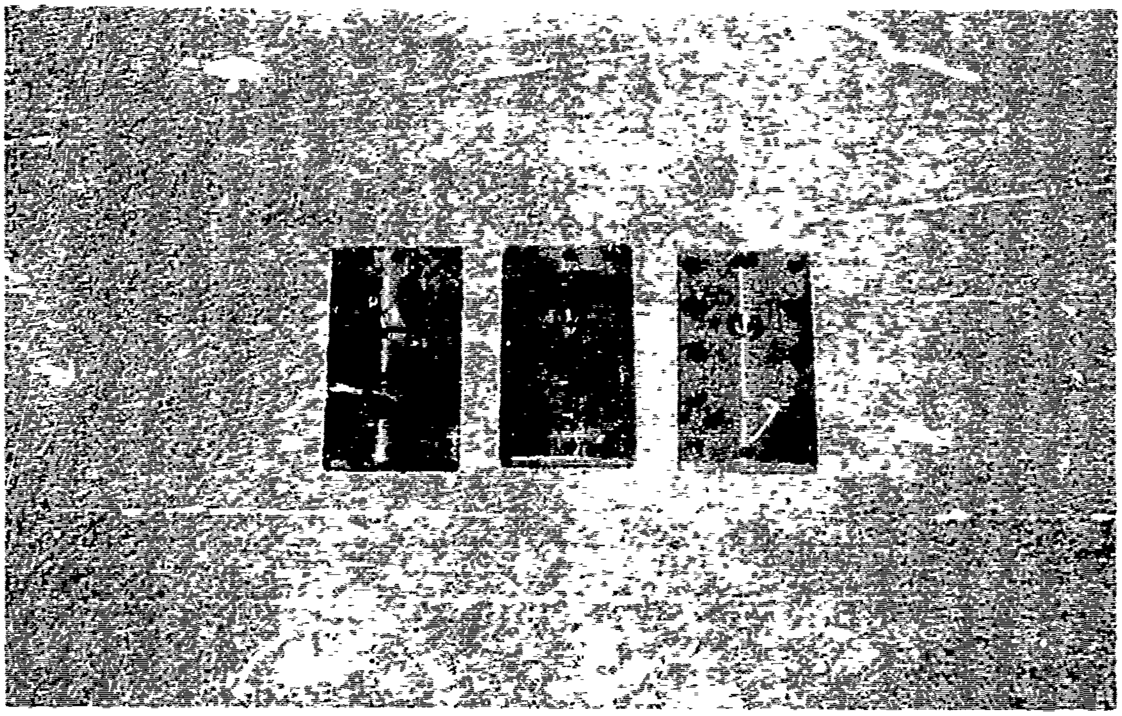


Figure 2. Typical Removable Orifice Plates

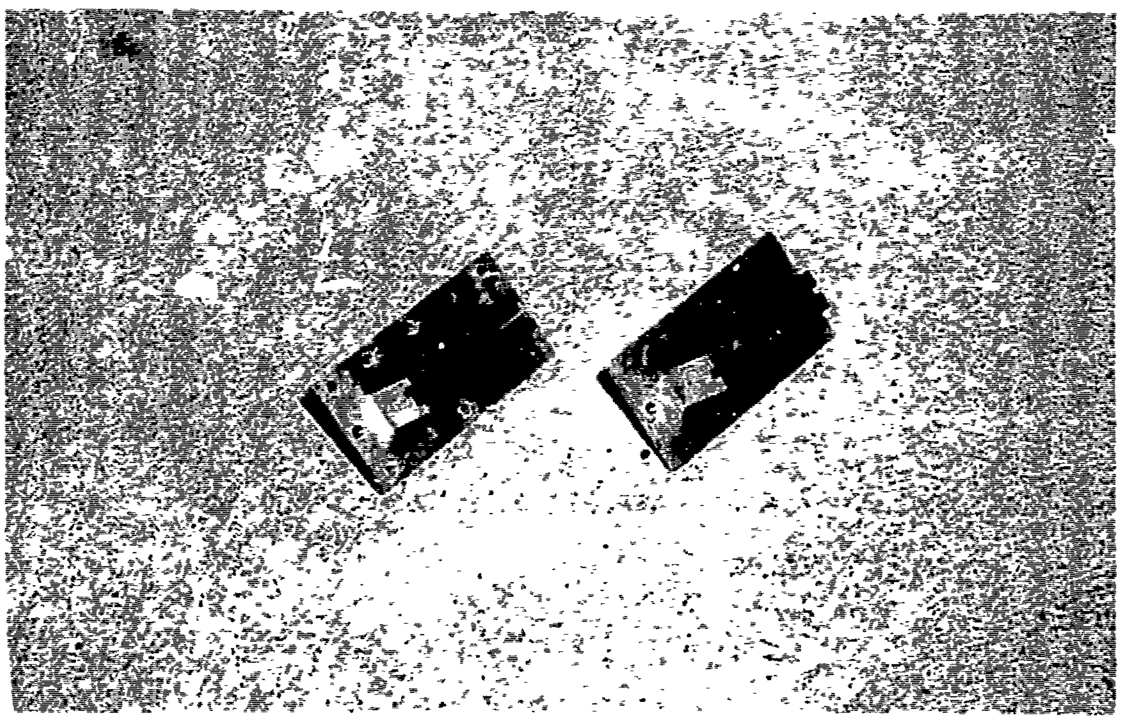
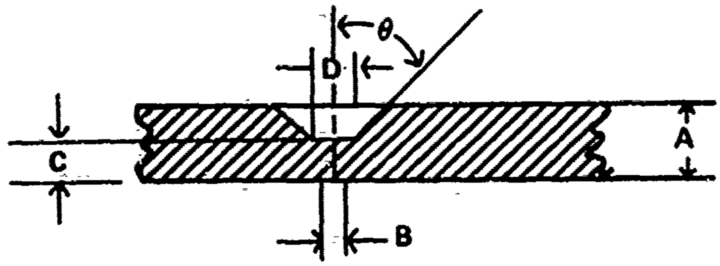


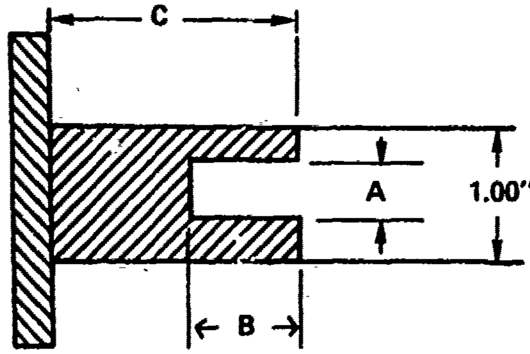
Figure 3. Typical Removable Back Plates

TABLE III. INJECTOR ORIFICE PLATE SPECIFICATIONS



Part Number	A	B	C	D	θ
X7047432-01	0.312	0.072	0.072	0.350	45°
-05	0.312	0.072	0.144	0.350	45°
-11	0.312	0.072	0.288	0.350	45°
-15	0.800	0.072	0.432	0.350	45°
-21	0.312	0.050	0.050	0.250	45°
-25	0.312	0.050	0.100	0.250	45°
-31	0.312	0.050	0.200	0.250	45°
-35	0.312	0.050	0.300	0.250	45°
-41	0.800	0.050	0.400	0.250	45°
-45	0.312	0.110	0.110	0.500	45°
-51	0.312	0.110	0.220	0.500	45°
-55	0.800	0.110	0.440	0.500	45°
-61	0.800	0.110	0.660	0.500	45°
-65	0.312	0.072	<0.0014	0.072	30"

TABLE IV. INJECTOR BACKPLATE SPECIFICATIONS



Part Number	A	B	C
X7047431-01	0.100"	0.168"	2.00"
-03	0.200"	0.114"	2.00"
-05	0.200"	0.150"	2.00"
-07	0.200"	0.240"	2.00"
-11	0.200"	0.300"	2.00"
-13	0.500"	0.140"	2.00"
-15	0.500"	0.240"	2.00"
-17	0.500"	0.320"	2.00"
X7047433	--	--	0"

approximately 3 inches in diameter at the down-stream end. In addition, there are three small ports located along the length of the chamber. Starting from the injector end, the first two ports are 0.172 inches in diameter and were used for pressure pickups. The third port is 0.609 inches in diameter and was used for chamber pressurization.

TEST SYSTEM

The test system is shown schematically in Figure 4 and photographically in Figure 5. It is constructed entirely of stainless steel components. Basically, it consists of three separate tanks connected to the injector/chamber assembly through appropriate valves and tubing. The run tank subsystem provides propellant flow to the injector. The flow rate can be controlled either by the run tank pressure or by the cavitating venturi in the system. The drain tank subsystem is used to maintain a gaseous nitrogen volume at the exit of the injector orifice in the chamber during each test run. The bypass tank subsystem is used to control the bypass flow rate and collect the bypassed propellant. The control of bypass flow rate during a test run was first attempted by use of a bank of several orifice/valve components of different sizes connected in parallel, but without success. This objective was subsequently fulfilled by varying the bypass tank pressure.

As shown in Figure 4, pressure, temperature and flow rate at various locations in the system can be monitored. Conventional instrumentation pickups (such as tubine flow meters, tube-mounted strain gauge pressure transducers and thermocouples) were used throughout the test program. The propellant flow rates in the feed system as well as in the bypass system were measured by a system of two flow meters connected in parallel to a special valve, such that the flow could be switched from one leg of the system to another while the run was in progress. This capability was incorporated in the test system for extending the useful range of flow measurements.

TEST AND DATA ACQUISITION PROCEDURES

Different test procedures were used between tests with and without cross-flow velocity (V_c) as a controlled test variable. For tests in which V_c was not a controlled test variable, the bypass tank subsystem was

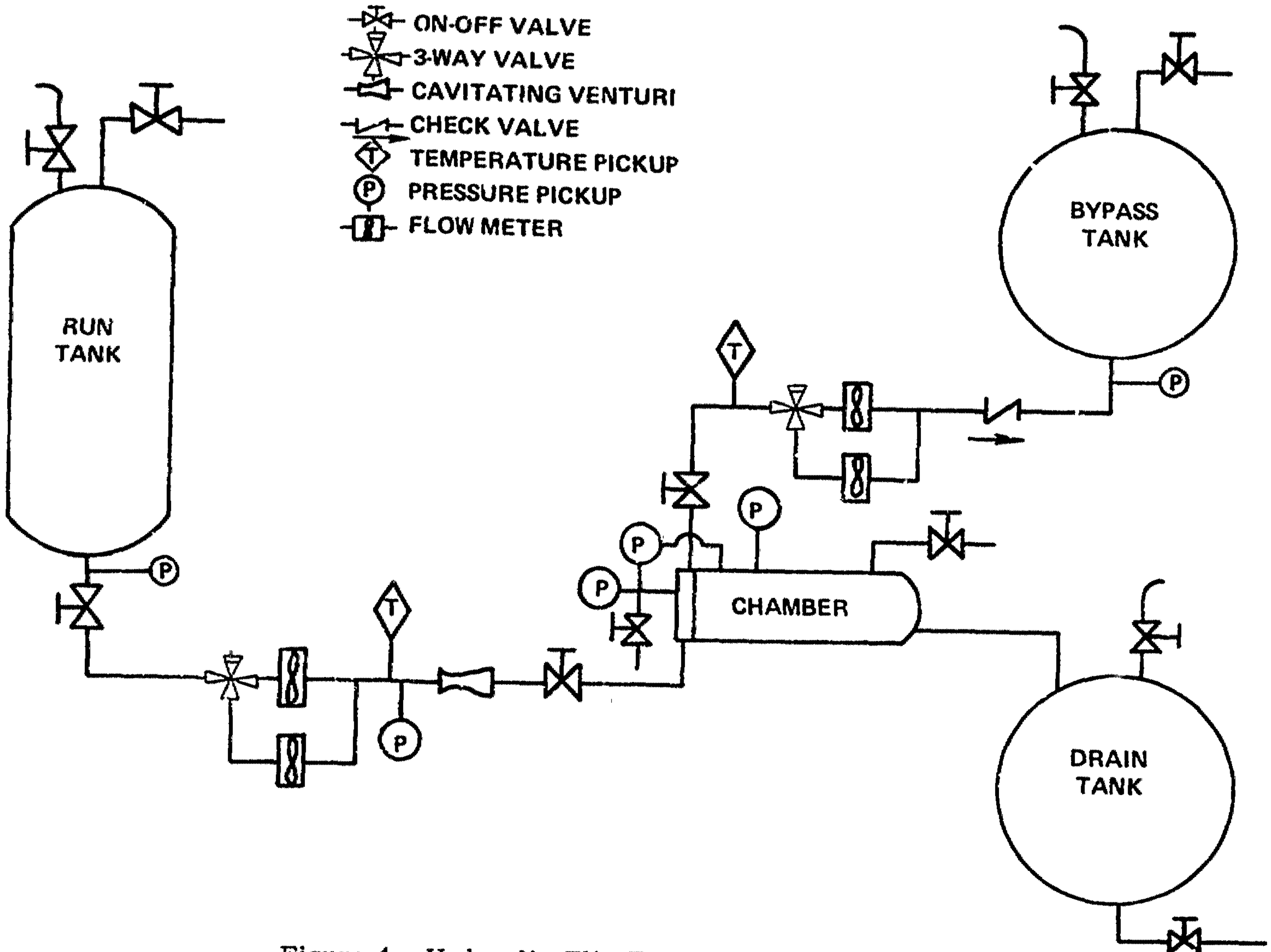


Figure 4. Hydraulic Flip Test System Schematic

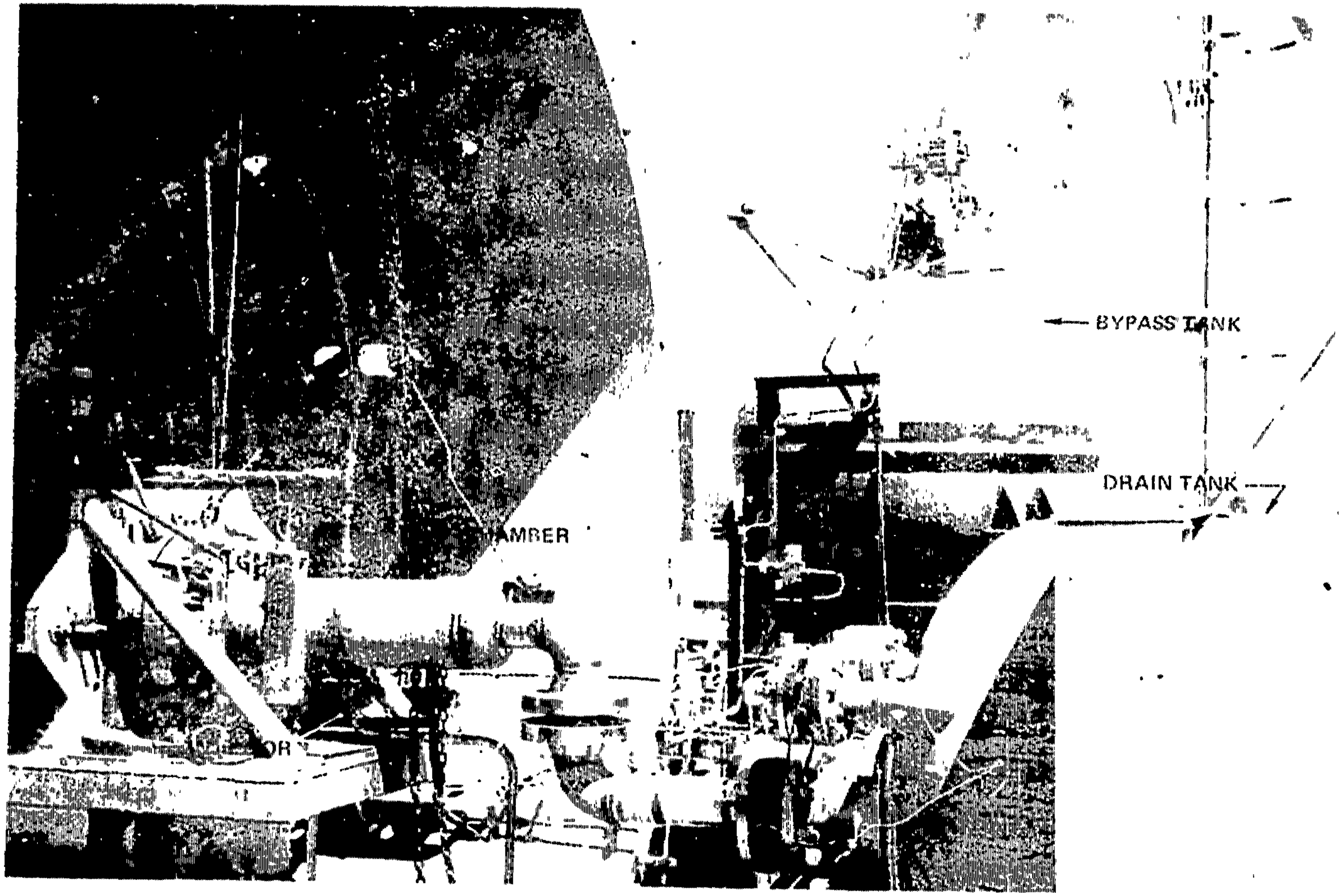


Figure 5. Hydraulic Flip Test System

isolated and not used. To conduct this type of testing, the chamber and the drain tank were pre-pressurized together with gaseous nitrogen to a desired pressure. The differential pressure across the injector orifice (ΔP_o) was then increased from a near zero value to a pre-selected maximum value (usually between 500 and 1000 psid) at a rate of approximately 3 psid per second. This was achieved by slowly increasing the run tank pressure. Once the maximum ΔP_o was attained, its value was decreased slowly by venting the run tank slowly. Pressures, temperatures and flow rates at locations shown in Figure 4 were recorded on digital tapes at a scanning rate of approximately 300 samples per second for the duration of each test run. From these data, ΔP_o and the corresponding orifice discharge coefficient (C_d) were computed and tabulated at one second intervals. The injector orifice pressure drop value at which hydraulic flip occurred (ΔP_f) could be easily obtained by noting a characteristic shift in C_d values to a lower level.

For the test series in which V_c was a controlled test variable, the V_c was maintained constant at a desired value throughout each test run. This was accomplished by using a cavitating venturi in conjunction with an appropriately selected injector back plate. As before, during each test the ΔP_o was increased slowly to a desired maximum value and then decreased slowly to zero psid. To do this, in view of the fact that the total flow rate to the injector must be maintained constant to ascertain a constant V_c, the bypass flow rate was varied accordingly. The variation of bypassed flow rate was effected by varying the bypass tank pressure. The procedures for the acquisition and reduction of test data were the same as described in the preceding paragraph.

The increase and decrease of ΔP_o during each test run were originally done in a step-wise manner with a change of approximately 2 to 8 psi per step. This method proved to be very time consuming and was later abandoned in favor of the continuous pressure ramping method.

SECTION IV

TEST RESULTS AND DISCUSSION

GENERAL

A total of 141 tests was conducted in accomplishing the test program described in Section II. Both water and nitrogen tetroxide were used as the test fluids. These tests include those specifically for data acquisition as well as those for system checkouts and system problems definition. A total of 92 of these tests, 42 conducted with water and 50 conducted with nitrogen tetroxide, produced useful data. Since the primary approach for each test run was to search for the hydraulic flip point (ΔP_f) by varying the pressure drop across the test orifice, the duration of each test was dependent upon the ease of occurrence of hydraulic flip. Thus, the test duration ranged from about 5 minutes to about 25 minutes. The test conditions and results of the data producing tests are provided in Tables V and VI for water and N_2O_4, respectively. The symbols used in these tables are defined in the nomenclature list. However, it should be mentioned here that: (a) "C_d range" refers to the range of C_d values found in each run, (b) the Reynolds Number (R_{ed}) is calculated based on the fluid velocity at the vena contracta as used in Ito's model (Reference 5), (c) "Max ΔP" refers to the maximum injector pressure drop value tested in the particular run, (d) the terminology used in the remarks column to describe the various types of hydraulic flip behavior is explained in the following subsection entitled "Hydraulic Flip Characteristics."

During the course of this experimental program, several side phenomena were encountered. They are briefly described below:

a. It was observed that the injection of nitrogen textroxide at low (25 psid or lower) differential pressure across the orifice into a chamber maintained at atmospheric pressure was unstable. This resulted in fluctuating values of C_d. This phenomenon is most likely caused by erratic but rapid vaporization of N_2Oat the orifice exit under these test conditions.

TABLE V. SUMMARY OF HYDRAULIC FLIP TEST RESULTS WITH WATER

Test No	D_o in	L/D	P_c psig	V_c ft/sec	T °F	Flip?	ΔP_f psid	T_f °F	C_{dB}/C_{dA}	C_d Range	ΔP_{pf} psid	R_{eo} At Flip Point or Max ΔP	Remarks
64	.051	2	203-202	0	74-76	Yes	310-367	76	.87/.69	.69-.90	324-331	1.27×10^5	Reluctant flip
69	.050	1	198-199	0	65-69	Yes	<14	65	--/.63	.60-.64	<3	1.64×10^4	Flipped at the start
49	.050	4	187-202	0	53-61	No	---	--	---	.71-.89	---	1.46×10^5	C_d decay; Max ΔP = 903 psid
50	.050	6	197-200	0	54-59	No	---	--	---	.75-.88	---	1.42×10^5	C_d decay; Max ΔP = 902 psid
51	.050	8	197-202	0	59-63	No	---	--	---	.75-.87	---	1.16×10^5	C_d decay; Max ΔP = 503 psid
7	.050	2	0	0	70-80	Yes	10-22	76	.87/.67	.67-.67	<6	3.23×10^4	Sharp flip
8	.050	2	0	0	64-74	Yes	21-23	68	.76/.61	.61-.76	<7	2.62×10^4	Sharp flip
65	.051	2	100-101	0	57-60	Yes	46-165	58	.94/.70	.68-.94	129-136	4.00×10^4	Reluctant flip
72	.051	2	100-102	0	---	Yes	155-158	--	---	---	107-110	---	Sharp flip; temp calibration N.G.
66	.051	2	396-401	0	55-59	No	---	--	---	.76-.90	---	5×10^5	C_d decay; Max ΔP = 900 psid
67	.051	2	591-596	0	64-68	No	---	--	---	.88-.89	---	1.95×10^5	Max ΔP = 950 psid
68	.051	2	786-796	0	61-66	No	---	--	---	.88-.89	---	1.83×10^5	Max ΔP = 699 psid
131	.051	2	200-203	5	118-126	No	---	--	---	.82-.90	---	1.91×10^5	C_d decay; Max ΔP = 284 psid
139	.051	2	200-201	5	99-102	Yes	371-380	101	.84/.67	.67-.86	327-330	1.86×10^5	Sharp flip
132	.051	2	202-203	10	115-116	Yes	387-392	116	.83/.68	.68-.92	368-374	2.19×10^5	Slight lazy flip
133	.051	2	202-205	15	110-112	Yes	386-396	112	.83/.67	.67-.89	189-194	2.12×10^5	Slight lazy flip
134	.051	2	200	20	83-85	Yes	417-423	85	.82/.67	.67-.87	295-300	1.62×10^5	Lazy flip
37	.072	2	201-204	0	59-67	Yes	289-304	64	.73/.55	.55-.74	270-282	1.20×10^5	Sharp flip
59	.072	1	199-200	0	65-76	Yes	<21	66	--/.61	.59-.63	<5	3.33×10^4	Flipped at the start
60	.072	4	196-198	0	65-69	No	---	--	---	.66-.78	---	1.60×10^5	C_d decay; Max ΔP = 506 psid
61	.072	6	197-200	0	55-56	No	---	--	---	.70-.78	---	1.41×10^5	C_d decay; Max ΔP = 502 psid
4	.072	2	0	0	73-81	Yes	16-17	79	.73/.58	.57-.77	<6	3.57×10^4	
5	.072	2	0	0	58-60	Yes	12-17	64	.72/.61	.61-.73	---	2.53×10^4	Reluctant flip
38	.072	2	396-402	0	53-68	No	---	--	---	.65-.79	---	1.98×10^5	C_d decay; Max ΔP = 989 psid

TABLE V. SUMMARY OF HYDRAULIC FLIP TEST RESULTS WITH WATER (Cont'd)

Test No	D_o in	L/D	P_c psig	V_c ft/sec	T °F	Flip?	ΔP_f psid	T_f °F	C_{dB}/C_{dA}	C_d Range	$\Delta P_{\mu f}$ psid	R_{ed} At Flip Point or MaxΔP	Remarks
39	.072	2	789-796	0	53-63	No	---	--	---	.77-.78	---	2.30×10^5	Max ΔP = 986 psid
135	.072	2	200	10	92-94	Yes	331-347	93	.75/.60	.60-.79	25-26	1.98×10^5	Lazy flip
136	.072	2	200	20	104-106	Yes	377-382	105	.68/.60	.60-.78	350-355	2.31×10^5	Lazy flip
20	.110	2	198-203	0	198-203	Yes	335-365	75	.69/.54	.54-.71	342-369	2.35×10^5	Sharp flip
71	.110	2	199-206	0	68-75	Yes	337-382	69	.77/.65	.62-.82	---	2.39×10^5	Lazy & reluctant flip
34	.110	2	197-199	0	50-54	Yes	<5	54	--/.62	.60-.62	<7	1.94×10^5	Flip at the start
35	.110	4	200-203	0	44-61	No	---	--	---	.69-.82	---	2.25×10^5	C_d decay; Max ΔP = 718 psid
36	.110	6	197-203	0	49-61	No	---	--	---	.67-.79	---	2.78×10^5	C_d decay; Max ΔP = 996 psid
2	.110	2	0	0	70	Yes	5-14	70	.77/.64	.64-.77	<6	2.75×10^4	Sharp flip
5	.110	2	0	0	65-76	Yes	12-13	69	.72/.65	.63-.77	<5	4.35×10^4	
6	.110	2	0	0	66-75	Yes	11-13	69	.81/.64	.64-.82	4-6	4.86×10^4	Reluctant flip
11	.110	2	24-28	0	87-99	Yes	17-23	93	.81/.62	.62-.81	---	7.76×10^4	Reluctant flip
22	.110	2	299-306	0	60-67	No	---	--	---	.76-.81	---	2.61×10^5	C_d decay, Max ΔP = 497 psid
23	.110	2	394-402	0	76-81	No	---	--	---	.76-.78	---	2.82×10^5	Max ΔP = 353 psid
32	.110	2	395-400	0	76-85	No	---	--	---	.79	---	3.16×10^5	Max ΔP = 443 psid
33	.110	2	789-797	0	75-86	No	---	--	---	.79-.81	---	4.32×10^5	Max ΔP = 845 psid
137	.110	2	200-203	10	103-104	No	---	--	---	.76-.80	---	3.43×10^5	Slight C_d decay; Max ΔP = 315 psid
133	.110	2	200-203	20	94-102	Yes	390-425	110	.73/.67	.63-.78	381-437	3.53×10^5	Lazy & reluctant flip

TABLE VI. SUMMARY OF HYDRAULIC FLIP TEST RESULTS WITH N_2O_4

Test No	D_o in	L/D	P_c psig	V_c ft/sec	T °F	Flip?	ΔP_f psid	T_f °F	C_{dB}/C_{dA}	C_d Range	ΔP_{Lf} psid	R_{ed} At Flip Point or Max ΔP	Remarks
96	.051	2	200-207	0	71-85	Yes	348-353	82	.84/.67	.67-.89	150-156	3.85×10^5	Lazy flip
130	.050	1	198-200	0	88-113	Yes	<3	88	--/.64	.61-.66	---	1.89×10^4	Flipped at start of run
101	.050	4	196-198	0	74-95	No	---	--	---	.72-.89	---	4.68×10^5	C_d decay; Max ΔP = 604 psid
102	.050	6	198	0	85-103	No	---	--	---	.79-.91	---	4.98×10^5	C_d decay; Max ΔP = 524 psid
103	.050	8	197-198	0	63-79	No	---	--	---	.73-.85	---	4.01×10^5	C_d decay; Max ΔP = 530 psid
115	.051	2	0	0	90-101	Yes	<28	92	--/.65	.66-.69	<7	9.76×10^4	Flow meter not steady below 28 psid
97	.051	2	102-103	0	72-82	Yes	172-177	77	.88/.65	---	<5	2.78×10^5	Flow meter had not steady out before flip
114	.051	2	99-100	0	86-89	Yes	161-167	86	.84/.67	.67-.86	<2	2.68×10^5	Sharp flip
98	.051	2	384-392	0	73-86	No	---	--	---	.68-.86	---	5.47×10^5	C_d decay; Max ΔP = 998 psid
99	.051	2	588-593	0	80-97	No	---	--	---	.84-.85	---	6.96×10^5	Max ΔP = 904 psid
116	.051	2	788-792	0	82-95	No	---	--	---	.85-.87	---	6.892×10^5	Max ΔP = 902 psid
128	.051	2	202-203	5	91-94	Yes	333-339	93	.85/.69	.66-.89	202-208	4.09×10^5	Lazy flip
127	.051	2	203	10	90-93	Yes	353-358	92	.81/.70	.70-.89	339-346	4.17×10^5	Lazy flip
126	.051	2	201-202	15	97-101	Yes	354-359	98	.84/.69	.68-.88	263-269	4.26×10^5	Lazy flip
125	.051	2	202	20	79-83	Yes	413-419	82	.82/.66	.68-.82	391-398	4.11×10^5	Sharp flip
82	.072	2	196-193	0	64-77	Yes	305-312	75	.80/.62	.62-.86	127-133	4.57×10^5	Sharp flip
91	.072	1	198-199	0	65-81	Yes	<22	65	--/.62	.59-.63	<4	9.04×10^4	Flipped at start of run
93	.072	4	192-197	0	72-79	No	---	--	---	.65-.81	---	4.33×10^5	C_d decay; Max ΔP = 518 psid
92	.072	6	197-199	0	72-83	No	---	--	---	.88-.91	---	6.55×10^5	Very slight C_d decay; Max ΔP = 518 psid
84	.072	2	0	0	77-81	Yes	<28	78	---	.63-.65	---	1.43×10^5	Flow meter not stabilized below 28 psid; Max ΔP = 361 psid
81	.072	2	100-101	0	68-85	No	85-92	74	.90/.68	.63-.90	<3	2.62×10^5	Sharp flip
83	.072	2	393-395	0	61-76	No	---	--	---	.72-.86	---	6.76×10^5	C_d decay; Max ΔP = 892 psid
75	.072	2	793-798	0	51-65	No	---	--	---	.82-.85	---	6.97×10^5	Max ΔP = 899 psid
76	.072	2	791-797	0	49-71	No	---	--	---	.81-.84	---	7.14×10^5	Max ΔP = 904 psid
89	.072	2	792-796	0	55-57	No	---	--	---	.78-.82	---	6.74×10^5	Max ΔP = 881 psid

TABLE VI. SUMMARY OF HYDRAULIC FLIP TEST RESULTS WITH N_2O_4 (Cont'd)

Test No	D_o in	L/D	P_c psig	V_c ft/sec	T ^oF	Flip?	ΔP_f psid	T_f ^oF	C_{dB}/C_{dA}	C_d Range	ΔP_{uf} psid	R_{ed} At Flip Point or Max ΔP	Remarks
118	.072	2	199-204	10	100-104	No	---	--	---	.76-.90	---	4.63×10^5	Max ΔP = 252 psid
124	.072	2	201-202	10	78-83	Yes	309-315	81	.76/.61	.60-.82	208-245	4.53×10^5	Lazy flip
119	.072	2	787-791	20	90-114	Yes	313-321	108	.74/.61	.60-.80	177-168	5.23×10^5	Lazy flip
123	.072	2	201-202	20	75-80	Yes	348-378	79	.73/.61	.61-.78	354-356	4.55×10^5	Reluctant flip
85	.072	Sharp Edge	792-797	0	78-86	Yes	<30	79	---	.61-.65	---	---	Flow meter not stabilized below 30 psid; Max ΔP = 504 psid
86	.072	Sharp Edge	793-797	0	66-72	Yes	<25	70	---	.61-.63	---	---	Flow meter not stabilized below 25 psid; Max ΔP = 503 psid
87	.072	Sharp Edge	793-796	0	69-79	Yes	<21	69	---	.61-.63	---	---	Flipped at start; Max ΔP = 502 psid
88	.072	Sharp Edge	781-792	0	65-68	Yes	<42	67	---	.61-.63	---	---	Flow meter not stabilized below 42 psid; Max ΔP = 507 psid
79	.072	1	791-793	0	64-78	Yes	<7	64	---	.61-.76	291-292*	5.58×10^4	*Occurred on ΔP up-ramp
80	.072	1	792-795	0	49-63	Yes	<15	58	---	.53-.74	278-282*	7.99×10^4	*Occurred on ΔP up-ramp
90	.072	1	787-797	0	59-68	Yes	<5	68	---	.60-.70	382-387*	5.04×10^4	*Occurred on ΔP up-ramp
73	.072	4	792-799	0	54-59	No	---	--	---	.74-.82	---	6.66×10^5	Max ΔP = 901 psid
74	.072	4	792-800	0	53-58	No	---	--	---	.77-.84	---	6.76×10^5	Max ΔP = 895 psid
77	.072	6	793-795	0	60-78	No	---	--	---	.81-.94	---	8.067×10^5	Max ΔP = 903 psid
78	.072	6	794-796	0	66-77	No	---	--	---	.89-.91	---	8.27×10^5	Max ΔP = 898 psid
94	.110	2	196-199	0	81-87	Yes	322-344	82	.76/.60	.60-.84	<2	7.28×10^5	Lazy flip
107	.110	1	197-199	0	72-89	Yes	<4	73	--/.62	.61-.63	<2	6.76×10^4	Flow meter not steadied out below 4 psid
108	.110	4	197-200	0	74-96	No	---	--	---	.69-.81	---	9.31×10^5	C_d decay; Max ΔP = 624 psid
109	.110	6	196-201	0	71-94	No	---	--	---	.68-.83	---	1.03×10^6	C_d decay; Max ΔP = 805 psid
104	.110	2	0	0	71-80	Yes	<26	79	--/.62	.61-.62	<4	2.05×10^5	Flow meter not steadied out below 26 psid
105	.110	2	392-393	0	74-92	No	---	--	---	.77-.82	---	9.71×10^5	C_d decay; Max ΔP = 601 psid
106	.110	2	789-808	0	65-85	No	---	--	---	.97-.98	---	---	C_d too high; no flip up to 810 psid

TABLE VI. SUMMARY OF HYDRAULIC FLIP TEST RESULTS WITH N_2O_4 (Cont'd)

Test No.	D_o in.	L/D	P_c psig	V_c ft/sec	T °F	Flip?	ΔP_f psid	T_f °F	C_{dB}/C_{dA}	C_d Range	ΔP_{nf} psid	R_{ed} At Flip Point or Max ΔP	Remarks
129	.110	2	798-804	0	86-90	No	---	--	---	.81-.90	---	1.38×10^6	No flip up to 901 psid
122	.110	2	199-202	10	65-74	Yes	343-402	67	.74/.64	.63-.80	345-395	6.83×10^5	Lazy & reluctant flip
121	.110	2	203-205	20	80-85	Yes	370-423	83	.74/.64	.63-.79	355-407	7.61×10^5	Lazy & reluctant flip

b. During the early testing of the 0.050 inch diameter orifice having a L/D of 2 at the 200 psig back pressure condition, it was found that hydraulic flip could not be induced even by raising orifice pressure drop as high as 850 psid. It was later found that there was a substantial number of burrs around the inlet edge of the orifice. The burrs were subsequently removed and the orifice then behaved normally as hydraulic flip was induced at conditions which were consistent with the results of other test orifices. The influence of orifice burrs on hydraulic flip behavior was clearly demonstrated in this case.

c. In early testing with water under atmospheric back pressure condition, it was found that by momentarily blocking the flow from the outlet side of the orifice, unflipping (transition from detached flow back to attached flow) could be induced. Lapedes (Reference 6) found that unflipping could also be induced by striking the upstream pipe sharply with a wrench when the orifice pressure drop value had decreased below the hydraulic flip point.

d. An abnormal behavior was experienced with the 0.072 inch diameter, L/D of 2 orifice tested at 800 psig back pressure. Flipped (detached) flow existed at the start of the run but the flow suddenly unflipped (re-attached) as the orifice pressure drop was increased to about 300 psid. This behavior was later confirmed twice by repeating this set of test conditions (see Table VI, test numbers 79, 80 and 90). A possible explanation of this abnormal behavior is that, under high back pressure conditions, high N_2O_4 flow rate into the back pressure chamber may have caused a dense cloud of N_2O_4 droplets and saturated vapor to exist at and near the orifice exit, and thus making it easy to re-wet the orifice wall. Re-wetting of the orifice wall is likely to enhance flow re-attachment.

HYDRAULIC FLIP CHARACTERISTICS

In analyzing orifice C_d data as a function of ΔP_o, several distinct types of hydraulic flip behavior were apparent (Figure 6). The first type

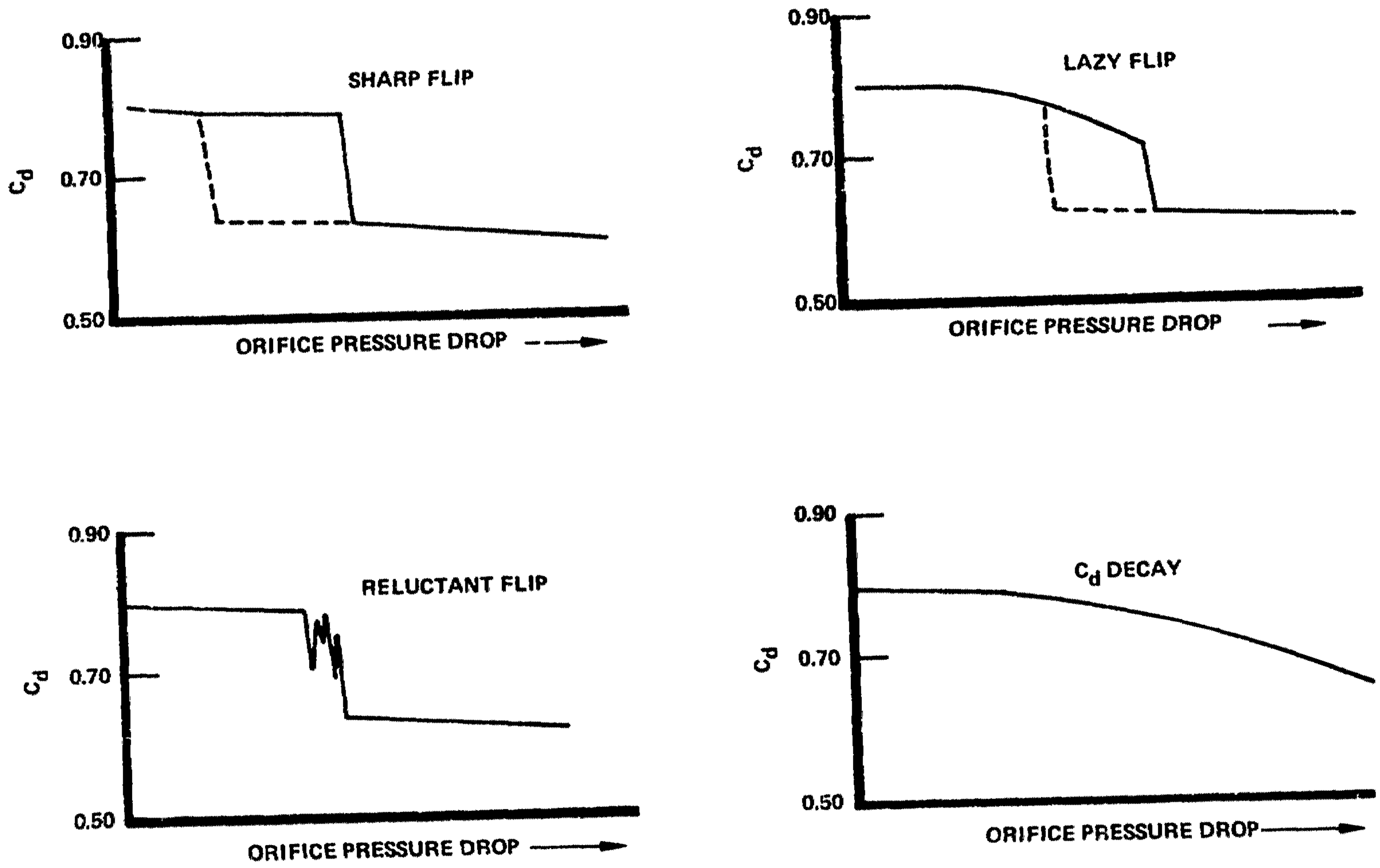


Figure 6. Typical Hydraulic Flip Characteristics

is termed "sharp flip," which is characterized by a sharp C_d transition from a higher level to a lower level as ΔP_o increased to the hydraulic flip point. On decreasing ΔP_o, C_d normally flips back (unflips) to the higher level at a lower ΔP_o transition value as depicted by the dotted line. Thus, a classical hysteresis loop for hydraulic flip is formed. It was often noted, however, that the C_d remained at the lower level as ΔP_o decreased slowly to near zero psid. In this investigation, as well as in some previous investigations (References 2 and 7), it was found that the unflip point (ΔP_o value at which a quick transition from detached flow back to attached flow occurs) is not predictable and not repeatable, and that the unflip point always occurs at or below the hydraulic flip point in terms of ΔP_o value.

For lack of a better descriptive term, the second type of hydraulic flip behavior is called "lazy flip." It differs from sharp flip only in that the C_d decreases steadily prior to the occurrence of hydraulic flip. For the same reason, the third type is referred to as "reluctant flip." It is characterized by a fluctuation of C_d values within the two C_d levels over a range of ΔP_o prior to settling down to the lower C_d level as ΔP_o increases. The fourth type is termed "C_d decay." Since no sudden change in C_d level is actually occurring, it is not a true example of hydraulic flip characteristics. However, this steady dropoff of C_d values as ΔP_o increased beyond a certain value cannot be ignored. The cause and effect of different types of hydraulic flip characteristics were not studied in this investigation.

EFFECT OF CHAMBER PRESSURE ON HYDRAULIC FLIP

The strong effect of chamber pressure on hydraulic flip is clearly revealed in Figure 7. In this figure, the orifice pressure drop value required for hydraulic flip to occur (ΔP_f) is plotted against orifice diameter (D_o) with back pressure (P_c) as a parameter. All plotted data were obtained for orifice L/D of 2 and near zero cross-flow velocity. The V_c actually ranged from about 0.3 to about 0.7 ft/sec. The vertical length of each data point reflects the range of uncertainty in ΔP_f, with the longer

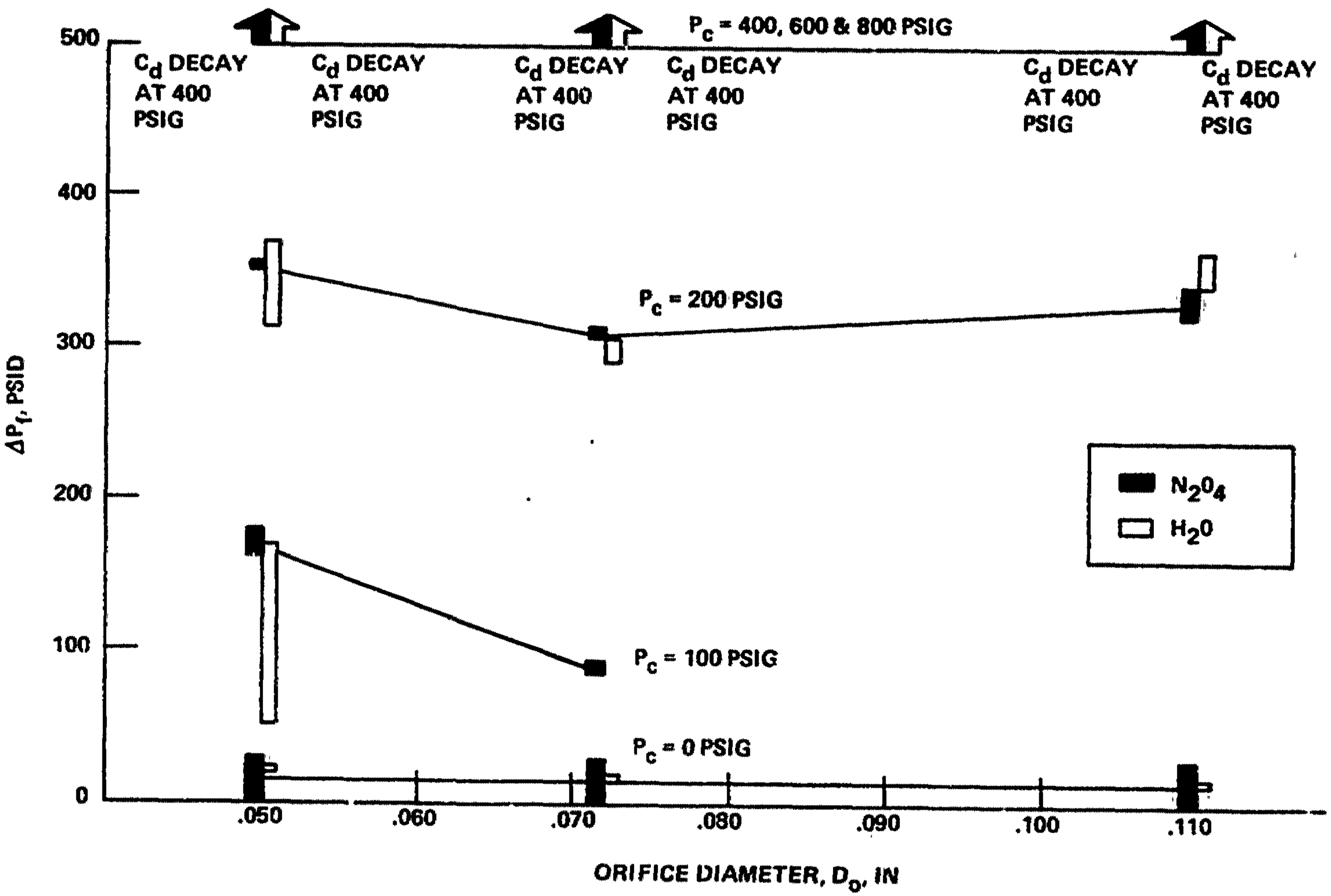


Figure 7. Effects of D_o on Hydraulic Flip with P_c as a Parameter, $L/D = 2$, $V_c = 0$ ft/sec

ones reflecting the occurrence of reluctant flips. It is readily seen that at the atmospheric P_c condition ΔP_f is below 30 psid for each of three orifice sizes tested. As P_c increased to 200 psig, the corresponding ΔP_f increased above 300 psid. When raising the P_c to 400 psig or higher, not a single case of hydraulic flip was encountered even at ΔP_o close to 1000 psid. At the 400 psid P_c level, however, the phenomenon of C_d decay was observed in all tests regardless of orifice size. At the 600 and 800 psig P_c levels, C_d remained fairly constant with respect to ΔP_o variations. This absence of C_d decay may be an indication of better flow stability with respect to the occurrence of hydraulic flip.

The experimental trend of ΔP_f increased with increasing P_c may be partially explained by the fact that higher ΔP_o is required to cause a fluid entering an orifice at a higher static pressure to cavitate at the vena co tracta. For a given fluid flow rate through a given orifice, higher P_c would necessitate higher fluid pressure at the orifice inlet. This, however, is not the whole story as inferred by Figure 14 in which the experimental data are compared to a cavitation flip model. Another contributing factor may be the possibility that higher P_c causes a denser mixture of fluid vapor and droplets to exist at and near the orifice exit. This would likely increase the tendency for the liquid to keep the walls of the orifice wet and the flow attached.

The experimental evidence of P_c effects on hydraulic flip implies that detached (flipped) flow would be likely to occur during the engine start transient of an engine operation and flow re-attachment (unflip) would take place as the chamber pressure increases toward its steady state value. However, it has been observed by the authors and other investigators (References 2 and 7) that the occurrence of flow re-attachment is unpredictable and often requires some induced flow disturbances.

EFFECT OF ORIFICE L/D ON HYDRAULIC FLIP

The effect of orifice L/D on hydraulic flip was experimentally investigated at a constant back pressure of 200 psig and at a cross-flow velocity of approximately zero ft/sec. The result is presented in Figure 8. For orifice L/D of 1, recorded data showed that detached flow always existed, although in some cases reliable data were obtained only at ΔP_o greater than 28 psid. This indicates that the use of orifice L/D of 1 or less in injector designs should be avoided. For orifice L/D of 2, the ΔP_f value increased to more than one and one-half times that of P_c -- a relative value far above that normally found in steady state liquid rocket engine operation. For orifice L/D of 4 and greater, hydraulic flip never occurred; not even when the ΔP_o was increased to a value near 1000 psid. However, C_d decay was observed in all cases.

Qualitatively, the experimental trend is consistent with the cavitation theory that the larger the orifice L/D, the higher the internal friction losses so that higher ΔP_o is needed to drive the static pressure at the vena contracta down to the fluid vapor pressure and induce flipping. However, it is apparent from Figure 14 that this theory can account for only a very small portion of the total effect. Therefore, it is reasonable to believe that there must be one or more other mechanisms by which hydraulic flip is influenced by orifice L/D. The length limited theory advanced by Ito (Reference 5) may account for another portion of the total effect, but it is still inadequate as discussed in a later subsection.

EFFECT OF CROSS-FLOW VELOCITY ON HYDRAULIC FLIP

In this area of investigation, a constant orifice L/D of 2 and a constant P_c of 200 psig were used. The variation of cross-flow velocity has only a mild effect on hydraulic flip as shown in Figures 9 and 10. The value of ΔP_f increases slowly with increasing V_c. Increasing the V_c from zero ft/sec to 20 ft/sec (a practical range of V_c found in operational liquid rocket engines) would only increase ΔP_f by approximately 12 percent.

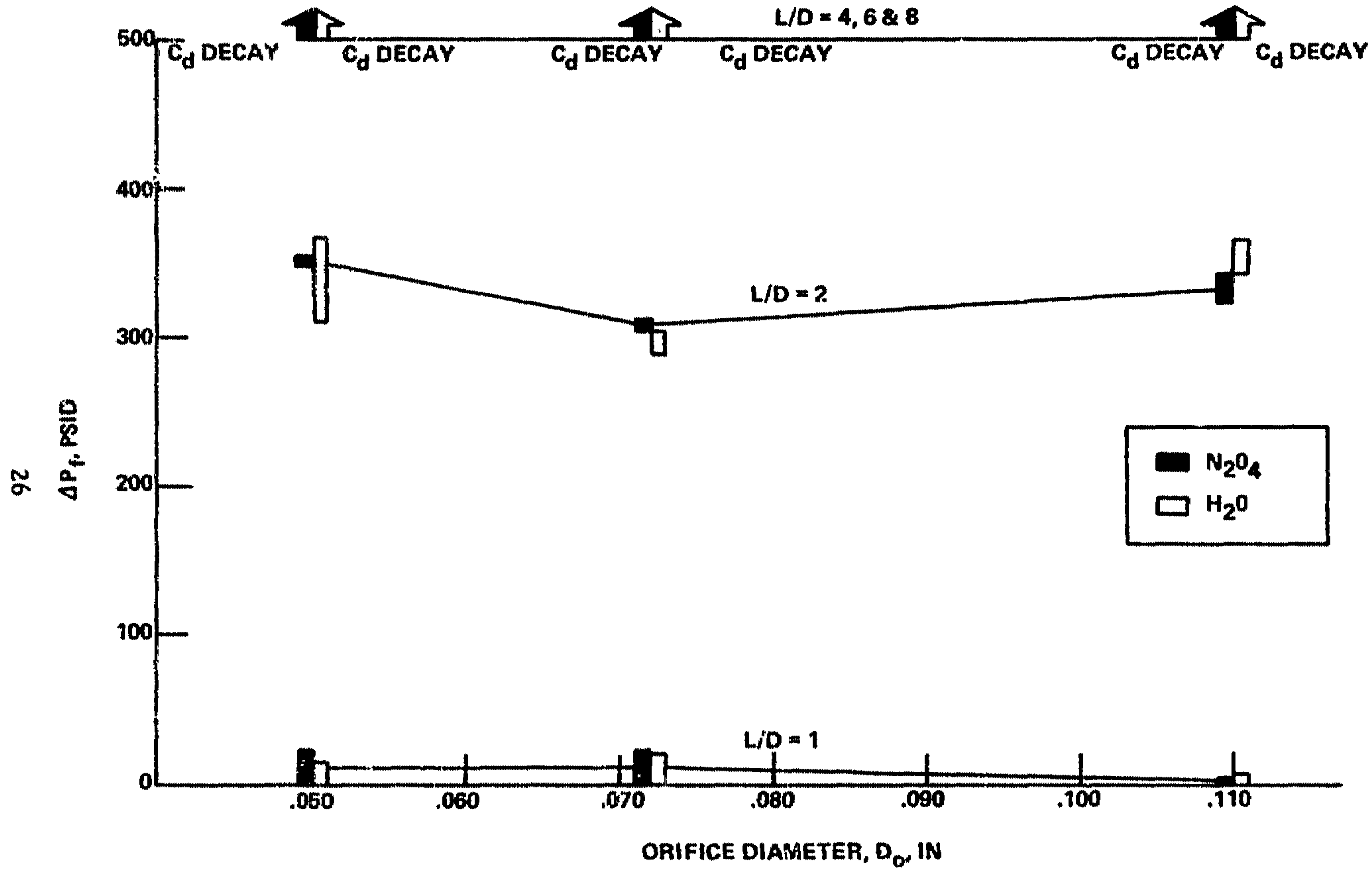


Figure 8. Effects of D_o on Hydraulic Flip with L/D as a Parameter, P_c = 200 psig, V_c = 0 ft/sec

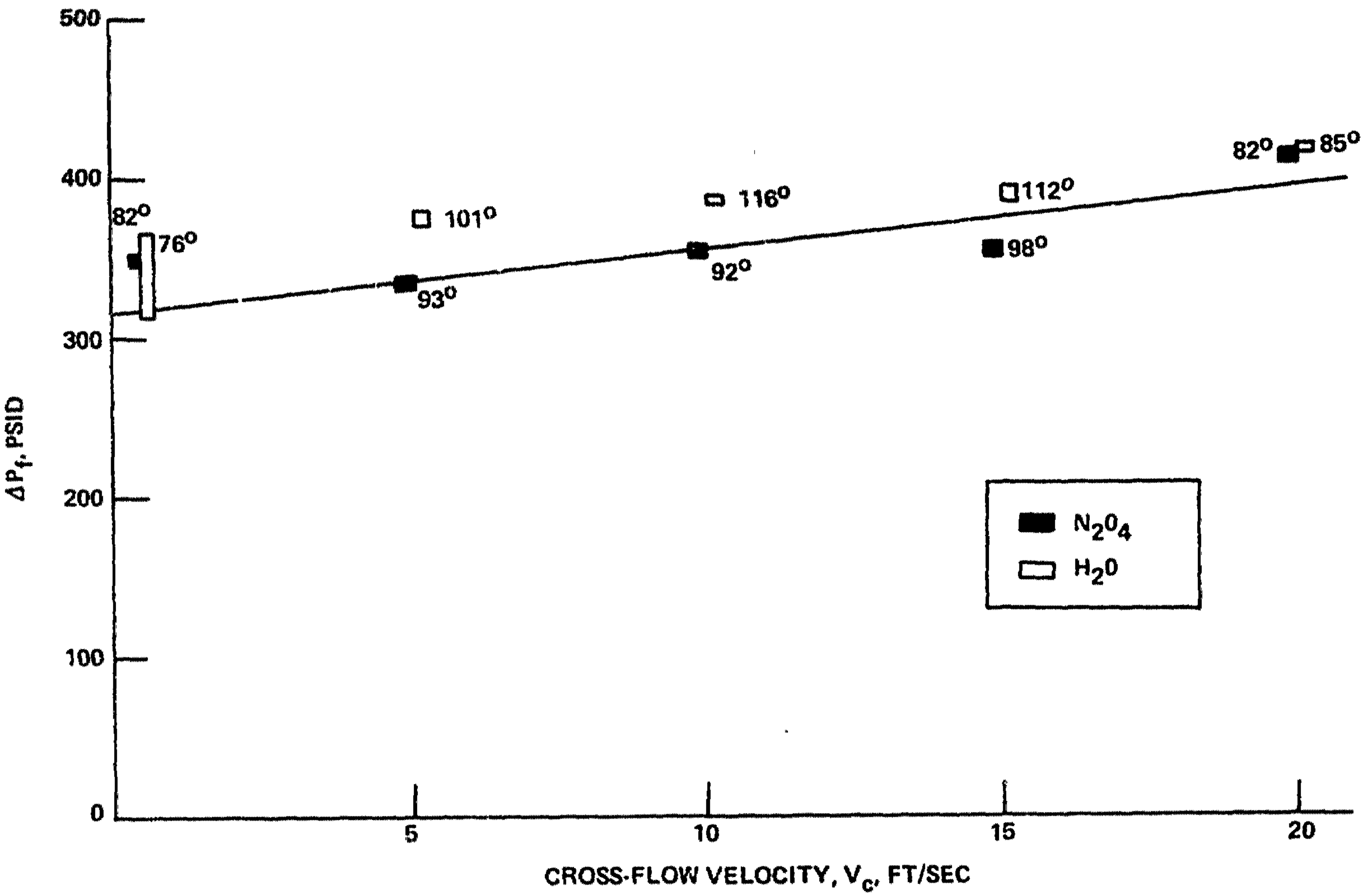


Figure 9. Effect of V_c on Hydraulic Flip, D_o = 0.050 in., P_c = 200 psig

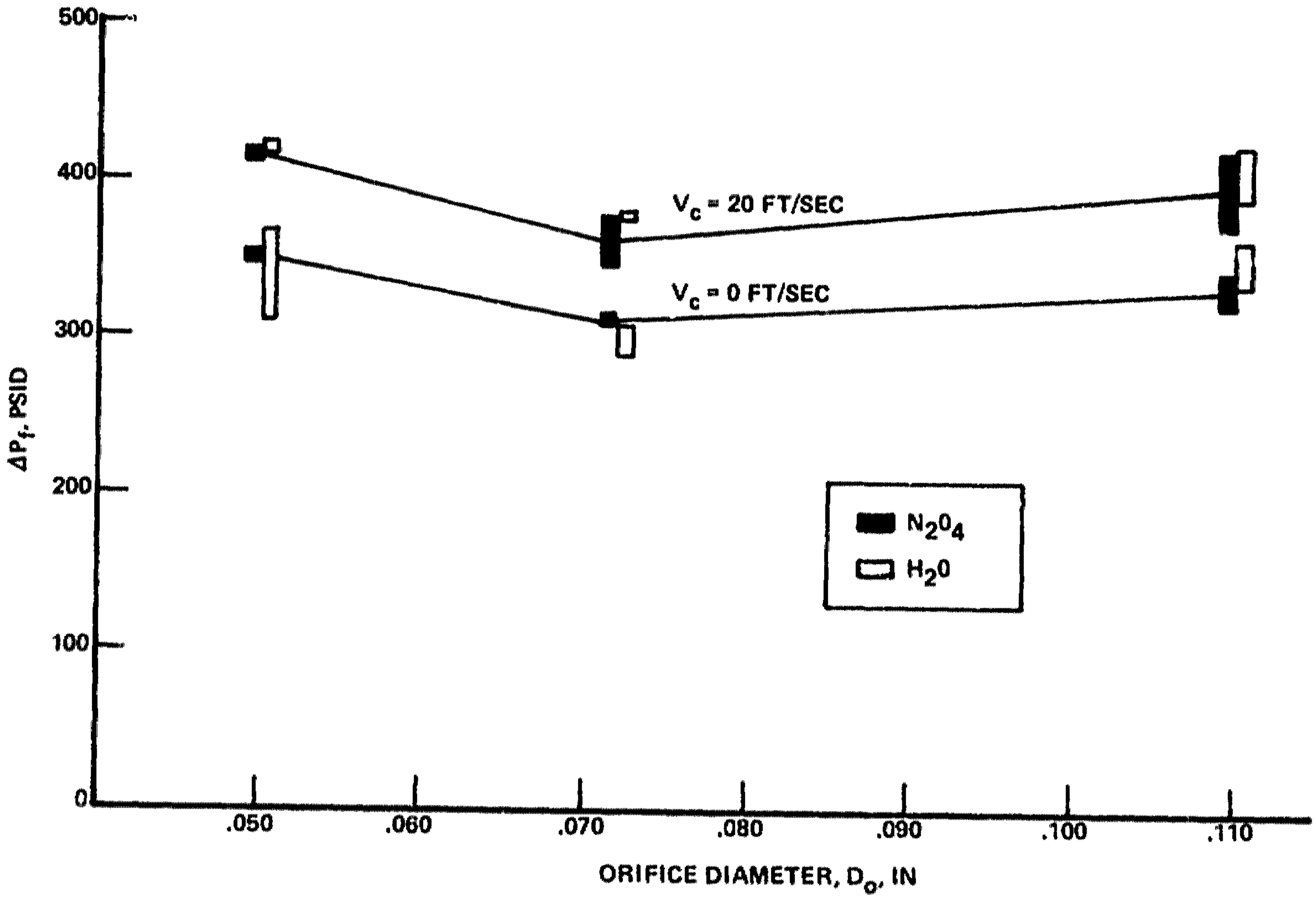


Figure 10. Effect of D_o on Hydraulic Flip with V_c as a Parameter, $L/D = 2$, $P_c = 200$ psig

The trend of increasing ΔP_f with V_c was also noted by Northup (Reference 2) when he experimented with water at atmospheric P_c condition using injector orifices with L/D values which ranged from 2 to 4.

The action of cross-flow velocity is likely to force the liquid in the orifice to first hit against one side of the passage and then reflect toward the opposite side. For an orifice having a moderate L/D, this action should result in a greater tendency to keep the orifice wall wet, and thus should increase the orifice resistance to hydraulic flip.

EFFECT OF ORIFICE DIAMETER ON HYDRAULIC FLIP

Figures 4, 8 and 10 show the effect of orifice diameter on ΔP_f as chamber pressure, orifice L/D and V_c were varied, respectively. It is seen that orifice diameter (D_o) had only a mild effect on hydraulic flip. Increasing D_o from 0.050 inches to 0.072 inches resulted in a mild decrease in ΔP_f. But further increase in D_o to 0.110 inches caused a slow increase in ΔP_f. This latter trend was unexpected and seems unreasonable. From the three figures, it is evident that the trend is consistent for the various series of tests using the same orifices. Therefore, the possibility of data acquisition problems was discounted. The orifices were subsequently examined under a 30X microscope and found that the inlet edge of the 0.110 diameter orifice was much rougher. Early program test experience has shown that burrs at the inlet edge of an orifice would cause ΔP_f to increase. Although the effect of the roughened inlet on ΔP_f cannot be quantified, its presence along with the early experience does lend credence to support the belief that ΔP_f decreases mildly with increasing orifice diameter as found with orifice sizes between 0.050 inch and 0.072 inch diameter. This trend is in agreement with that previously observed by Lapedes on tests conducted with water under atmospheric back pressure conditions (Reference 6).

EFFECTS OF TEST FLUID AND FLUID TEMPERATURE ON HYDRAULIC FLIP

As shown in Figure 11, the physical properties (such as density, viscosity and vapor pressure) of water and N_2O_4 are greatly different. However, the injector pressure drop values required for hydraulic flip to occur are nearly the same for these two fluids. This result is illustrated in Figures 7 through 10 in which the values of ΔP_f for the two fluids are compared as injector orifice design and operating parameters (such as D_o, L/D, V_c and P_c) are varied. The lack of fluid property effect on hydraulic flip was also noted by Northup (Reference 2) in his experimentation with water, alcohol and carbon tetrachloride at atmospheric back pressure condition. Thus, it seems adequate to use water as a simulant for normal (non-cryogenic) propellants in hydraulic flip testing.

As previously stated, the temperature of the test fluids was not controlled. However, two N_2O_4 tests repeated on different dates revealed qualitatively that ΔP_f decreases with increasing N_2O_4 temperature. This experimental evidence is shown in Figure 12. From these limited data, it is not possible to accurately establish the rate change of ΔP_f with respect to the fluid temperature, T. However, if a linear rate is assumed, the rates would be 1.17 psig/^oF and 1.59 psig/^oF for the two cases. The fluid temperature is given for each data point in Figure 9. A straight line is drawn through the 92^oF and 93^oF N_2O_4 data points for reference. In a qualitative sense, it can be seen that correcting the rest of the N_2O_4 data point to 92^oF or 93^oF temperature would tend to reduce the data scatter. Undoubtedly, at least some of the data scatter encountered was due to fluid temperature effect.

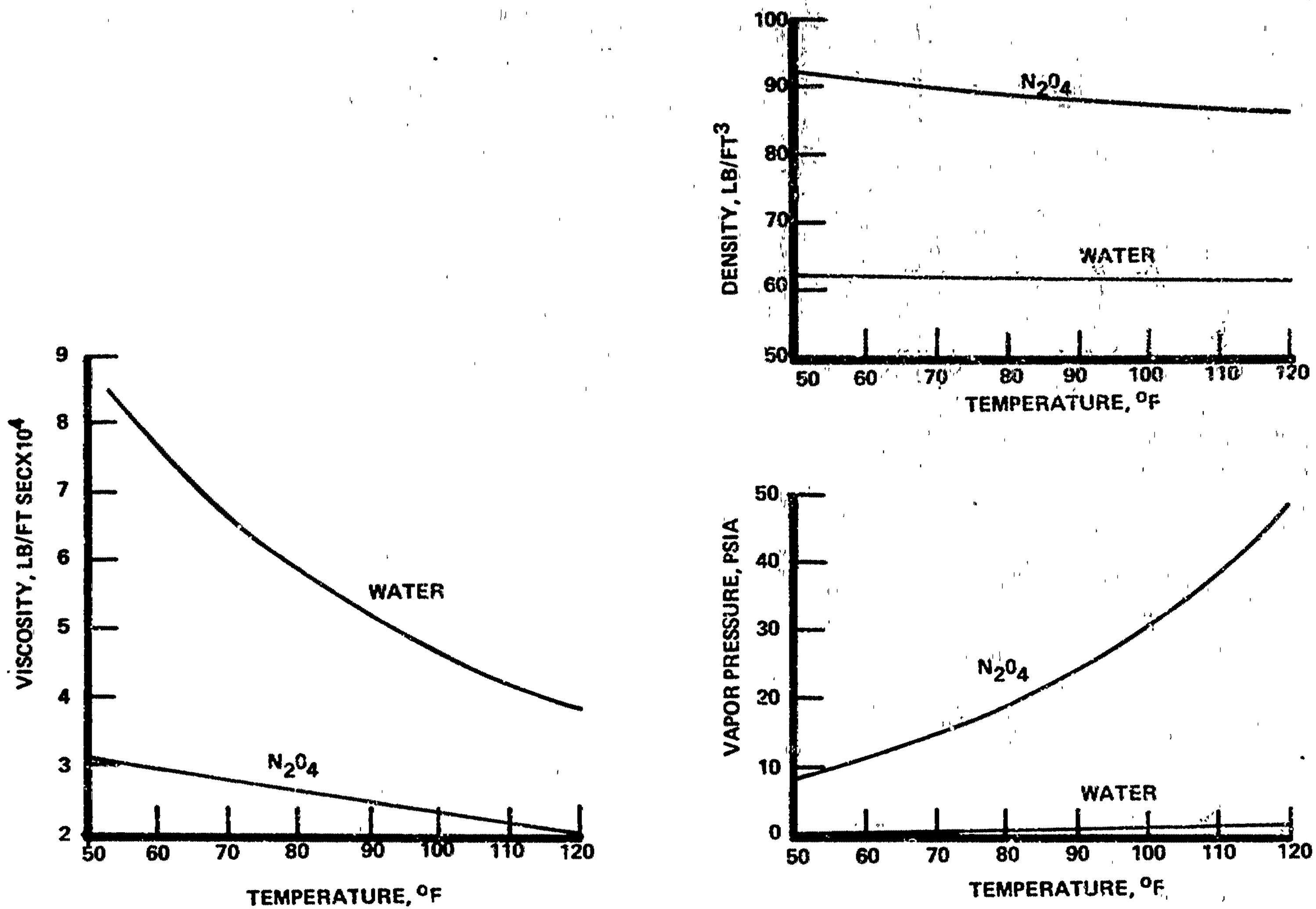


Figure 11. Properties of Water and N_2O_4

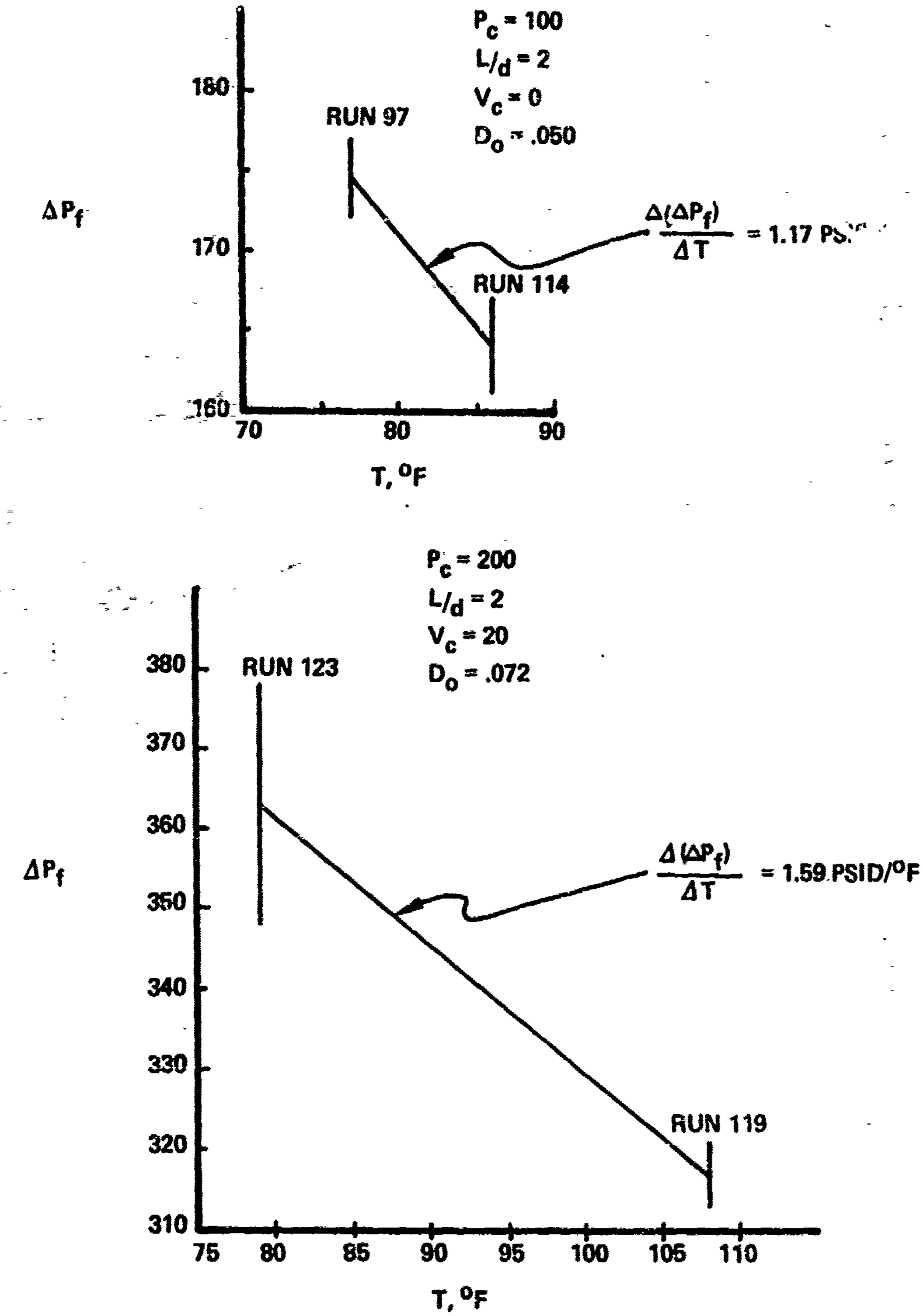


Figure 12. Effects of N_2O_4 Temperature on Hydraulic Flip

COMPARISON WITH ITO'S LENGTH LIMITED HYDRAULIC FLIP MODEL

Based on the hypothesis that detached flow may occur in orifices with insufficient L/D, Ito (Reference 5) developed a model for both laminar and turbulent boundary layer flows. The analytical expressions for this model are:

$$\text{For laminar flow - } (L/D)_{cr} = \left[\frac{1 - \sqrt{C_{co}}}{11.28}\right]^2 R_{ed}$$

$$\text{For turbulent flow - } (L/D)_{cr} = \left[\frac{1 - \sqrt{C_{co}}}{0.75}\right]^{1.25} R_{ed}$$

Where:

$(L/D)_{cr}$ = Critical orifice L/D below which detached flow will occur.

C_{co} = Contraction coefficient at the vena contracta.

R_{ed} = Reynold's number based on orifice diameter.

This model is presented graphically in Figure 13 by two straight lines; one for laminar flow and the other for turbulent flow. The model predicts that the conditions below each of the lines should result in detached flow. Experimental data points for both water and N_2O_4 are plotted in the same figure for comparison. It is obvious that the model is inconsistent with the experimental results. The experimental data show no occurrence of hydraulic flip for orifices have L/D of 4 or greater and flipped (detached) flow always prevails for orifices having L/D of 1. For orifices having L/D of 2, the results are mixed. This strong L/D effect on hydraulic flip is not adequately described by the model. The mixed data from tests with L/D of 2 result primarily from the variation in P_c. The strong effect of P_c on hydraulic flip, as discussed earlier in

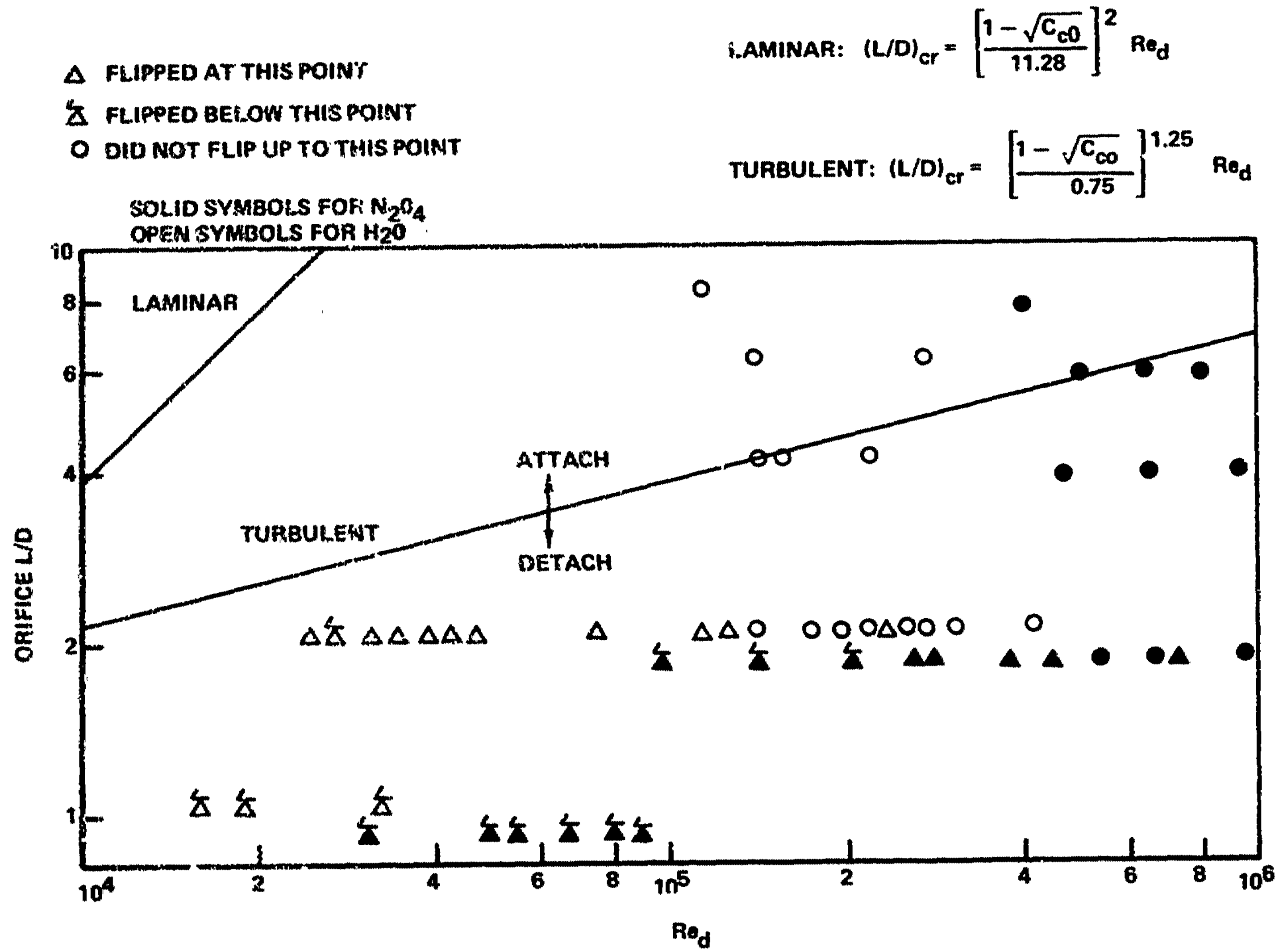


Figure 13. Comparison With a Length Limited Hydraulic Flip Model

this report, is totally unaccounted for by the model. Perhaps this is the most significant deficiency of the model.

Another observation is that the model seems to over-emphasize the dependency of hydraulic flip on R_{ed}. It has been shown earlier that, under identical test conditions, the values of ΔP_f for both water and N_2O_4 are nearly the same. But in terms of R_{ed}, at an identical ΔP_o, water flow has a relatively lower R_{ed} due to higher fluid viscosity. The model incorrectly predicts less tendency for water to flow detached.

COMPARISON WITH CAVITATING FLIP THEORY

Many investigators (References 1, 4, 5 and 6) have modeled hydraulic flip based on a fluid cavitation theory. A representative of these is the one described by Ito as follows:

$$\Delta P_f \geq \frac{1 - \bar{n}}{\bar{n} - f\frac{L}{D} C_{co}^2} \left(P_c - P_v\right)$$

Where:

ΔP_f = the orifice pressure drop value required for hydraulic flip to occur

f = friction factor

L = orifice length

D = orifice diameter

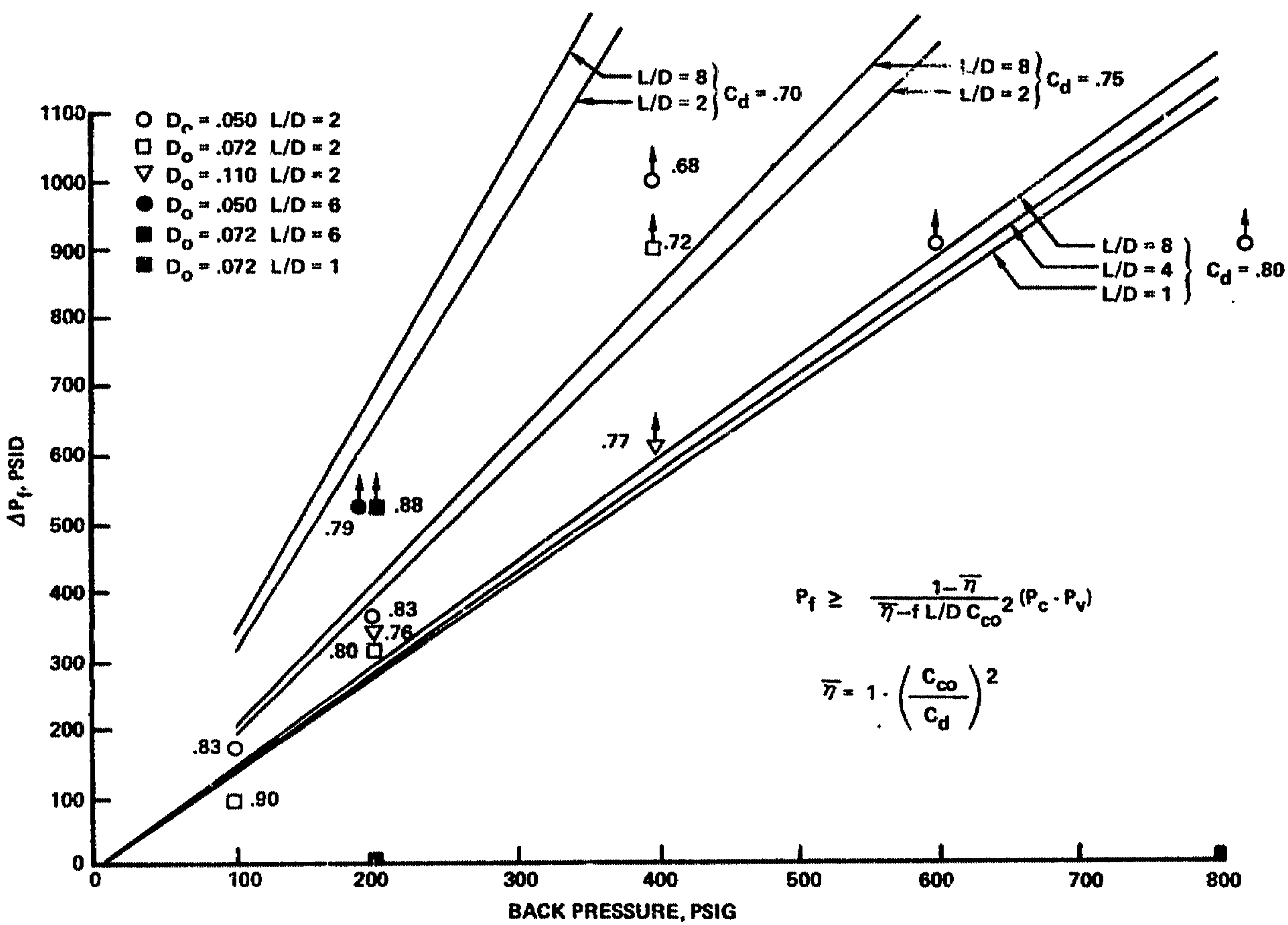
P_c = chamber pressure

P_v = vapor pressure

$\bar{n}$ = $1 - \left(\frac{C_{co}}{C_d}\right)^2$

C_d = orifice discharge coefficient

This expression is represented graphically in Figure 14 by three groups of straight lines with each group corresponding to a different value of C_d. The lines within each group reflect different values of orifice L/D. The model predicts a strong influence of C_d on the occurrence of hydraulic flip. However, the predicted influence of L/D is almost negligible. The predicted small influence of L/D is not supported by experimental data which show a very strong L/D effect. From Figure 14 it can be seen that the experimental data reasonably follow the theoretical trend only for L/D of 2. The C_d values for most data points are provided in the graph so that experimental evidence of C_d effect can be detected. It seems evident that the main deficiency of this model is its inability to describe the strong influence of orifice L/D on hydraulic flip.



$$P_f \geq \frac{1-\overline{\eta}}{\overline{\eta}-f\,L/D\,C_{co}{}^2}\,(P_c - P_v)$$

$$\overline{\eta} = 1 - \left(\frac{C_{co}}{C_d}\right)^2$$

Figure 14. Comparison With a Cavitation Induced Hydraulic Flip Model

SECTION V
CONCLUSIONS AND RECOMMENDATIONS

1. Water can be used as an acceptable propellant simulant for noncryogenic propellants in experimental hydraulic flip investigations.

2. Hydraulic flip is a strong function of orifice L/D and chamber pressure. Increasing either of these parameters will increase the orifice pressure drop value for hydraulic flip to occur.

3. Hydraulic flip is a mild function of cross-flow velocity and orifice diameter. Increasing the cross-flow velocity or decreasing the orifice diameter tend to increase the orifice pressure drop value for hydraulic flip to occur.

4. For $L/D \geq 2$ and $P_c \geq 200$ psig, hydraulic flip is not expected to occur in the range of injector pressure drop values normally found in steady state liquid rocket engine operation. However, the probability of hydraulic flip occurring in the engine start transient and persisting into steady state operation was not investigated but should be considered in practical situations.

5. The theoretical models evaluated are inadequate for hydraulic flip prediction.

6. In practical injector design considerations with respect to hydraulic flip, the possible effects of the following parameters, which were not investigated in this work, should be considered: (1) chamber gas density, (2) orifice orientation, (3) propellant temperature, (4) injector orifice plate temperature, (5) transient flow, and (6) injector structural dynamics.

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